Canopy geometry and the interception of PAR in a temperate deciduous forest : an interpretation of hemispherical photographs

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Introduction

The interest in interactions between plant canopies and the environment, for a wide range of spatio-temporal scales, has increased drastically in recent times. Taking the examples of forests, Hutchinson and Hicks (1985) and Jarvis et al. (1990) provide useful readings. This concern rests, in part, on an accelerating sophistication of techniques and methods (see e.g. Pearcy et al., 1989; Goel and Norman, 1990) and on a considerable effort of modeling (e.g. Ross, 1981; Hari et al., 1985; Russell et al., 1989a), to improve the understanding of the structural and functional complexity of plant canopies. In particular, the canopy structure and the radiation regime are so tightly coupled (Chartier, 1966; Anderson, 1971; Lemeur and Blad, 1974) that the one can be used to predict the other. The basic approach to derive the canopy geometry is the inversion of a radiative transfer model (Norman and Campbell, 1989). Twomey's work (1977) is a classical presentation of inversion methods.

The aim of the present study is to explore the structure of a forest canopy by means of hemispherical photographs. Their quantitative interpretation leads to : i) ascertain the canopy geometry, through the foliage area and angle distributions; ii) predict the interception of PAR by the foliage. The light regime within the canopy will be approached in two ways : i) by using a model, with its inherent simplifying assumptions; ii) by using the raw data and directly analyzing the heterogeneity of the plant cover.

1. Materials and methods

1.1 Study site

A montane Beech forest (*Fagus silvatica* L.) was chosen at Aubure Vosges, France. It is an almost pure stand, homogeneous at eye, with some interspersed individuals of White Fir (*Abies alba* Mill.). Latitude 48° 12' N, longitude 7° 11' E, altitude 1050m, slope 15°, aspect 15° (NNE). Stand age 120 yrs, density 429 stems ha^{-1}, median height 22m, median d.b.h. 33cm, basal area 44m^2 ha^{-1} (Asael, 1990). The densely stocked canopy is an essential feature of the stand (Fig. 1).
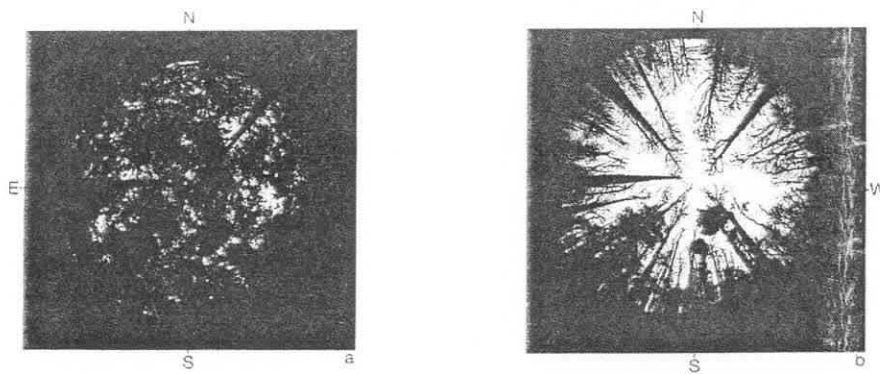

Figure 1. Hemispherical photographs of the Beech canopy (photosite 12). **a** : fully leafed phenoseason. **b** : leafless phenoseason (some White Fir crowns appear interspersed among Beech trunks). Percent of visible sky : 3.7 (**a**), 40.6 (**b**). LAI : 4.02 ± 0.12 [sample s.e. of estimate (**a**)], 1.86 ± 0.09 (**b**).

1.2 Method

Hemispherical canopy photography has been widely used in ecological studies, primarily to assess the light regime beneath plant canopies (Anderson, 1964, 1971). The simultaneous treatment of the canopy geometry and the distribution of light is more recent (Bonhomme, 1976; Leong *et al.*, 1982; Torquebiau and Walter, 1987).

Canopy photographs, using either a fish-eye lens or telephotos (Bonhomme *et al.*, 1973; Takenaka, 1987), are essentially binary (foliage black, sky white, on positive images) in order to yield the sought gap fraction. Like any technique, it has potentials and limits, depending on the accuracy required and the aim of the study. For instance, the solar beam penetration is assumed to be parallel through the canopy holes. There is no penumbra. However, the penumbral effect can be estimated (Miller and Norman, 1971; Hutchinson, 1975; Oker-Blom, 1984, 1986). In high canopies, the apparent

dimensions of the leaves are usually very small in relation to the resolution power of the optical system and the emulsion. Very small canopy openings, so important in forests in order to account for the penumbra (Evans, 1966; Anderson and Miller, 1974; Alexandre, 1982), will vanish on the emulsion or produce a halo effect.

1.3 Sampling and data processing

Two sets of photographs were taken along a transect in the forest at the location of rain gauges, 3 to 5m apart from each other, at 50cm above the ground. Sixteen photosites in July 1989 and 15 in March 1990 were sampled to account for the leafed and leafless phenoseasons, respectively. The camera, equipped with a fish-eye lens Nikkor 8mm and a view angle of 180°, was carefully levelled and oriented for true North. A high contrast Kodak Microfile film was used with a red filter. The raw data from each photograph consisted of a matrix with 18 intervals of 5° zenith angles and 24 sectors of 15° azimuth angles which contained the gap fraction.

PAR is understood as QPAR, quantum irradiance (Varlet-Grancher et al., 1989). The interception of PAR was considered for clear sky only. Equivalences of 4.6 mole quanta MJ^{-1} of EPAR (energy irradiance) and 2.3 mole quanta MJ^{-1} of total solar radiation were used at the daily level (Russell et al., 1989b). Optical properties of the foliage and the soil in the PAR waveband were derived from measurements by Baldocchi et al. (1985). Calculations were performed at hourly intervals of time, then daily integrated.

1.4 Theoretical background

1.4.1 Canopy geometry

Foliage area indexes (LAI) and foliage average inclination angles (ALA) were based on the Poisson distribution model of the gap fraction over the whole range of angles. A closed canopy was assumed horizontally homogeneous, with phytoelements azimuthally distributed at random and opaque to solar radiation. This one-dimensional model has been widely used (Nilson, 1971; Ross, 1981; Campbell and Norman, 1989; Norman and Campbell, 1989). Lang's work (1986, 1987, 1991) provided the basis for the calculations. These results on the canopy geometry were completed by measurements of the canopy openness. A weighted canopy openness (Chazdon and Field, 1987) was determined as the fractional penetration of diffuse radiation by standard overcast sky (Anderson's (1964) diffuse site factor).

1.4.2 Radiative transfers (PAR)

Model approach. In Norman's radiative transfer model (Norman, 1979), LAI is a key parameter to obtain the direct and the diffuse components of the canopy radiation field. The assumptions of a spherical distribution with an azimuthal randomness of foliage elements, and an isotropic sky radiance distribution, are required in the model. However, the assumption of a spherical distribution was modified presently, in order to account for the variable ALA (see Jarvis and Leverenz, 1983, p. 247). The beams of the

primary radiation field are supposed to penetrate unmodified through the holes of the canopy. The complementary radiation field (Sinoquet *et al.* in this book), due to the radiation scattering by the foliage and the reflection on the ground (Hutchinson and Matt, 1976) is taken into account by the model.

Direct approach. This approach does not require assumptions on the canopy geometry. Instead, the radiation intercepted (canopy radiation field) depends upon values calculated for each canopy element involved, over the whole hemisphere and along the solar tracks. To ascertain the primary radiation field, a clear sky diffuse radiance distribution (McArthur and Hay, 1981) was accounted for, using Dogniaux analytical equations (Dogniaux, 1975; Ducrey, 1975). The complementary radiation field was estimated by using an iterative technique (Norman *et al.*, 1971; Baldocchi *et al.*, 1985).

In the following sections, the expressions "model estimates" and "azimuthal data estimates" will refer to these approaches. They correspond approximately to the two ways the canopy geometry may be modeled : as homogeneous or heterogeneous (e.g. Sinoquet *et al.*, 1990). In the former, the azimuthal information is lost, whereas in the latter, the structural heterogeneity of the plant cover is fully explored.

2. Results and discussion

The gap fraction, as recorded by canopy photographs, is only an instantaneous image on the time scale of forest dynamics. However, in the present study, over days and seasons it may be reasonably considered as constant : from May through October and from November through April (Fig. 1).

2.1 Canopy geometry

Values of the fractional weighted canopy openness ranged from 0.03 through 0.11 in the leafed period, and from 0.32 through 0.51 in the leafless period. Averages were 0.06 ± 0.01 (s.e. of sample mean) and 0.40 ± 0.01, respectively. Their local variation followed the ecological gradient from the high forest to a small tree-fall gap (Fig. 2a). The relatively low values in the leafless period express the high density of trunks, twigs and the presence of interspersed White Fir.

Variations of LAI and ALA are presented in figure 2b. Averaging over the plot gave LAI 4.09 ± 0.10 in the leafed period (range 3.61 ± 0.15 (sample s.e. of estimate) through 4.99 ± 0.17) and 1.81 ± 0.06 in the leafless period (range 1.44 ± 0.08 through 2.28 ± 0.09). In the leafed period, values of ALA varied widely (range 32°0 ± 5°8 (sample s.e. of estimate) in the high forest through 74°3 ± 4°8 in the tree-fall gap). They paralleled the changes of canopy openness. These results emphasize the geometrical gradient between a "horizontal canopy", characterizing the leafed high forest and a more "vertical canopy", centered on the tree-fall gap. In the leafless phenoseason, ALA showed a more regular pattern (range 56°9 ± 2°3 through 77°2 ± 1°7), typical of the leafless condition.
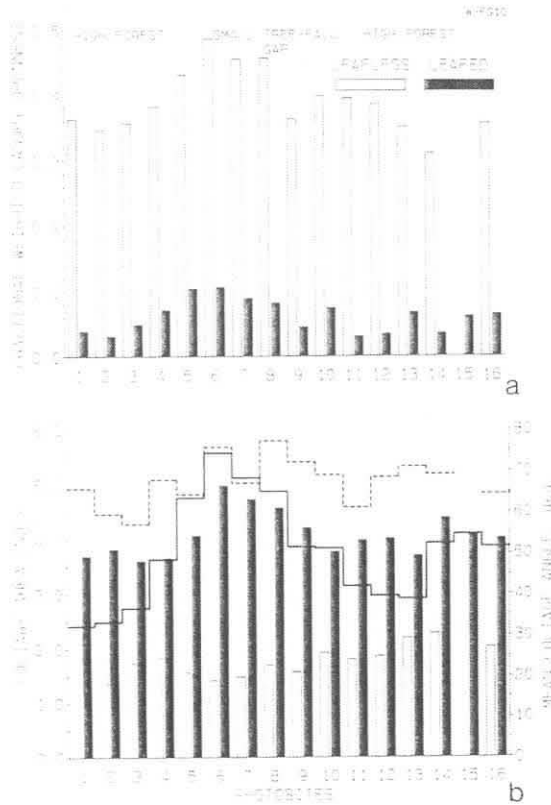
Figure 2. Horizontal variation of the canopy geometry along the ecological gradient from the high forest through a small tree-fall gap, in leafed and leafless conditions. **a** : fractional weighted canopy openness. **b** : LAI and ALA (solid line, leafed period; dashed line, leafless period).

Higher values of LAI (leafed period) in the tree-fall gap zone may be explained by its small size and by the dense lateral growth around its border. The gap fraction is much more reduced at median and lower elevations than in equivalent positions of adjacent high forest sites. These values were largely compensated by high ALA. Due to the presence of White Fir crowns (Fig. 1), LAI of the leafless period cannot be taken as true bark or stem area indexes. LAI in the presently studied Beech stand were lower than those found one km apart in a sheltered and fertile site on a southern slope : in that higher stature canopy LAI reached 6 (Walter, unpublished). The estimates of LAI were consistent with values found elsewhere in Beech forests (e.g. Satoo, 1970; Ellenberg, 1983; Lemée, 1987). However, values of ALA cannot be compared accurately, considering the scarcity of reported data from forests (e.g. Anderson, 1981; Hutchinson et al., 1986).

2.2 Interception of PAR

2.2.1 Effect of the topography on the daily estimated incident PAR, Q

PAR irradiance was computed for the horizontal reference surface and the actual topography of the stand, using a clear sky radiance distribution. Figure 3a is self-explanatory.
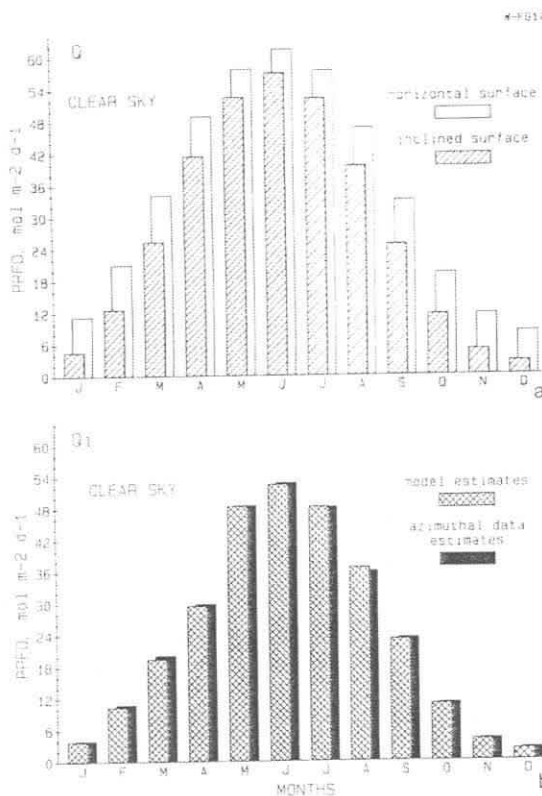

Figure 3. Monthly variation of the PAR regime, above and inside the Beech canopy (21st of each month). All values corrected for slope and orientation. **a** : topographic effect on the radiation Q received by the stand (clear sky radiance model). **b** : Norman's model estimates and azimuthal data estimates of the intercepted radiation Q_i; values averaged over 15 (leafless phenoseason) and 16 (leafed phenoseason) photosites.

2.2.2 Effect of the diffuse sky radiance model on the daily estimated incident PAR, Q

Although not detailed here, the choice of the isotropic sky radiance model versus the clear sky radiance model for the diffuse component of the global radiation (Hutchinson et al., 1980) had little influence on the predicted PAR received by a level or a slightly inclined surface above the canopy, when the sun was not too low. In effect, hourly differences are smoothed out by the daily integration. Since the isotropic sky radiance is much simpler to calculate, it is preferred to the clear sky models for estimates of PAR.

Conversely, on steep slopes, or at the hourly level, the influence of the relief and the spatial heterogeneity of the canopy will be better taken into account by the more realistic heterogeneous sky radiance model.

2.2.3 Norman's model and azimuthal data estimates of the daily intercepted PAR, Q_i

Q_i was calculated as incident radiation minus transmitted radiation (Varlet-Grancher *et al.*, 1989). Results in figure 3b (PAR intercepted) and 4b (interceptance i) emphasize the close agreement between both approaches. Differences of Q_i between both approaches were not significant over the year at the level 0.05 (two-tailed paired t-test, $t_s = 1.797$). The same conclusion applies to i for the leafed period ($t_s = 1.874$) and the leafless period ($t_s = 0.385$), respectively. Although not discussed here, the introduction of ALA instead of the spherical distribution assumption, basically required by the model, placed model estimates in the closest agreement with azimuthal data estimates.
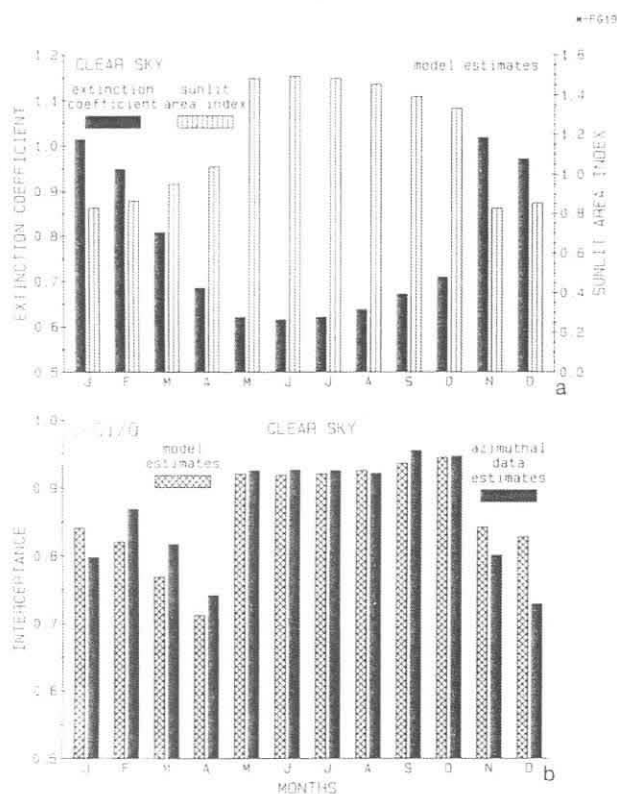

Figure 4. Monthly variation of the PAR regime (21st of each month). All values corrected for slope and orientation. Values averaged over 15 (leafless phenoseason) and 16 (leafed phenoseason) photosites. **a** : model estimates of the extinction coefficient K_{PAR} and the sunlit area index F_S. **b** : interceptance i, model estimates against azimuthal data estimates.

In both approaches, the coefficients of variation of Q_i were low (about 2% for each leafed month and on average 6% for the leafless period). This suggests a homogeneous

behaviour of the stand in the reception of solar radiation, at least at the spatio-temporal scale considered. In Summer time, the daily regime of PAR appears very stable from one photosite to the other, irrespective of the approaches. The abrupt changes from April to May and from October to November indicate that the leafing and leaf-fall transition periods were not accounted for.

2.2.4 Extinction coefficients K_{PAR} and sunlit foliage area indexes F_s

The extinction coefficients and the sunlit foliage area indexes were calculated at every photosite for each month (Fig. 4a). Values of K_{PAR} regularly decrease from January through April whereas the sunlit area indexes increase with higher sun altitudes. The slope and the NNE orientation of the stand intensify the extinction of radiation in Winter time. The maximum was reached in November and January (K_{PAR} approx. 1.02) and not in December ($K_{PAR}=0.97$) as expected. This is due to the very short sunfleck duration in the stand in December. For example, with a maximum sun elevation angle of 18°, the daily length of sunfleck was only 1mn at photosite 12, compared with the potential daylength of 488mn (21st December), a transmission of 0.002. Almost only diffuse radiation is transmitted evenly through the canopy. K_{PAR} decreases rapidly with higher sun altitudes and reaches a minimum of 0.615 in June. The interpretation of F_s is straightforward. With LAI supposed constant over both phenoseasons, the variation of F_s within each period is due only to the varying position of the sun. The high values found in the leafless period (0.83 through 1.04) express the large extension of trunks and branches. This annual course of the PAR regime characterizes the temperate deciduous forest biome. The values of K_{PAR} agree well with those found elsewhere for both phenoseasons and underline the importance of bark surfaces in the radiation interception (e.g. Federer, 1970; Jarvis and Leverenz op. cit.; Baldocchi et al., 1984).

Conclusion

The good agreement between model estimates and azimuthal data estimates of the PAR interception suggests that Poisson model-derived LAI and ALA were reliable. In fact, no clumping of the phytoelements was detected in the dense Beech canopy. However, if clumping becomes a dominant feature in the canopy, for example in thinned or senescent Beech stands, predictions may be significantly improved by using non-random models (Nilson, 1971), whose parameters can be determined on hemispherical photographs (Neumann et al., 1989; Chen and Black, 1991; Chen et al., 1991). In spite of the absence of direct measurements for comparison, our results on the seasonal dynamics of the foliage and the light regime within the canopy were consistent with those reported in the literature for other temperate deciduous forests.

Acknowledgments

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